AEDC-TR-69-125

A METHOD FOR DETERMINING THE BULK PROPERTIES OF ARC-HEATED ARGON

R. J. Bryson

ARO, Inc.

June 1969

ROCKET TEST FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

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FOREWORD

The work reported herein was sponsored by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 61102F, Project 8951, Task 05.

The research was conducted by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, under Contract No. F40600-69-C-0001. The work was conducted under ARO Project Numbers RW5806 and RW5910 in the Propulsion Research Area (R-2E-2) of the Rocket Test Facility (RTF) from July 1967 to September 1968, and the manuscript was submitted for publication as partial results of these research efforts on May 6, 1969.

The work discussed here was first reported in a University of Tennessee Space Institute thesis under the guidance of Dr. W. T. Snyder. The author also wishes to acknowledge W. K. McGregor, Jr., and R. C. Bauer for their counseling during the course of this investigation and J. H. Fox for his work in obtaining the method of characteristics solution of the potential flow equations.

This technical report has been reviewed and is approved.

Michael G. Buja	Edward R. Feicht
2nd Lt, USAF	Colonel, USAF
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ABSTRACT

The total temperature and total pressure of argon gas at the exit of a direct-current arc jet are determined by using a corrected version of the one-dimensional, constant-area, heat-addition analysis. The corrections are formulated in terms of the thrust produced by the arc jet and are determined by measuring the actual thrust. To assess the validity of properties determined in this manner, a method of characteristics solution of the general potential flow equations was obtained for the flow field resulting from a free expansion of the gas from these properties into a low pressure. Mach numbers given by this solution were then compared with those derived from measured pitot pressures in the expanded stream. The agreement between the predicted and the average measured values of Mach number is within about 4 percent. This would allow the average static temperature to be predicted within about 8 percent and the average static pressure to be predicted within about 18 percent. This indicates that the method of predicting the gas properties at the exit of the arc jet can be used as a first approximation.

CONTENTS

APPENDIXES

I. ILLUSTRATIONS

NOMENCLATURE

A	Nozzle cross-sectional area
a	Intercept on the ideal thrust axis
b	Intercept on the measured thrust axis
C_ℓ	Loss coefficient defined by Eq. (4)
F	Thrust produced by the arc jet
M	Mach number
m	Slope of straight-line approximation for ideal thrust
$\dot{m}$	Gas mass flow rate
n	Slope of straight-line approximation for measured thrust
p	Static pressure
p_o	Total or stagnation pressure
R	Specific gas constant
r	Nozzle radius
T	Static temperature
T_o	Total or stagnation temperature

u	Velocity in the direction of the gas stream centerline
x	Coordinate in the direction of the gas stream centerline
y	Coordinate perpendicular to the gas stream centerline
z	Flow parameter defined by Eq. (18)
γ	Ratio of the specific heats of the gas
ρ	Density

SUBSCRIPTS

1	Station at the entrance to the arc-jet anode nozzle
2	Station at the exit of the arc-jet anode nozzle
c	Test cell conditions
i	Ideal values
m	Measured values
RH	Obtained by Rayleigh heating analysis
x	Upstream of normal shock
y	Downstream of normal shock

SECTION I
INTRODUCTION

The arc-jet plasma generator has been used extensively as a means for producing high enthalpy gas flows. One of the most frequent uses in basic studies of plasma properties is to produce a supersonic flow field by allowing a free expansion of the gas into a low pressure region (Ref. 1, for example). The interpretation of measurements made in the expanded gas stream would be greatly aided if bulk gas properties throughout the flow field were known. This is especially true when the gas stream is to be studied by spectroscopic techniques or by electrostatic probes because knowledge of the gas particle density is very important. Since the method of adding energy to the gas in such a device is a complex process, it is not obvious that bulk gas properties can be calculated by the ideal gas-dynamic relations. However, if these relations could be made to yield good approximations for the properties, the ease of calculation might outweigh any possible increase in accuracy produced by a more difficult exact solution including real gas and plasma effects. It is the purpose of this study to substantiate the usefulness of a method for approximately determining argon gas properties at the exit of a d-c arc jet (Ref. 2). This is done by using conditions determined at the exit of the arc jet as starting conditions for a potential flow calculation of the free-jet properties. Comparison of Mach numbers obtained from the potential flow calculation and Mach numbers measured in the free jet will indicate how well the method of Ref. 2 will furnish starting conditions for the potential flow theory and also how well the free jet produced by the arc jet conforms to that predicted by the potential flow theory.

The method in question is applied to an arc jet with a constant-area, sonic-nozzle anode. It is based on making corrections to the exit values of total temperature and total pressure obtained by using the ideal, constant-area, heat-addition analysis. The corrections are defined in terms of the ideal thrust and the actual thrust produced by the arc jet and can, therefore, be determined by measuring the force on the arc jet. If correction factors are determined over the range of operation for an arc jet of a particular design, then exit conditions of the gas can be determined without the necessity of measuring the force each time. This was shown in Ref. 2.

Mach numbers in the expanded gas stream are predicted by solving the potential flow equations by the method of characteristics. Conditions determined at the arc-jet nozzle exit are used as the starting conditions. These values of Mach number are compared with values obtained from measured impact pressures by using normal shock relations. The

agreement between the calculated and the measured values is within about 7 percent. When calculating the static temperature and static pressure, this error in Mach number leads to errors of about 13 and 32 percent, respectively. However, when the measured values of Mach number are averaged at each axial station, the agreement with predicted values is within about 4 percent. This error in Mach number leads to errors in the static temperature and static pressure of about 8 and 18 percent, respectively. Possible explanations for the disagreement are discussed.

SECTION II
APPARATUS AND PROCEDURE

2.1 TEST CELL

The low pressure test cell shown in Fig. 1 (Appendix I) was a vertically mounted section of cylindrical pipe, 30 in. in diameter, and closed on one end. The other end was connected to two mechanical vacuum pumps which could maintain the cell at approximately 2 mm of mercury with a secondary gas flow of approximately 0.005 lb/sec. The cell was fitted with a Plexiglas® viewing port and a port used for mounting the test body.

2.2 ARC JET AND INSTRUMENTATION

The arc jet used was of the Gerdien type and is shown in Fig. 2. The front and back plates are made of brass, and the main body is a water-cooled copper jacket. Assembly of the arc jet is accomplished by using screws which pass through electrical insulators in the front and back plates and are threaded into the main body. The main body and the front and back plates are separated by an O-ring seal. This provides a good pressure seal as well as electrical insulation so that the main body is electrically floating. The rear plate contains a pressure-sealed opening for the cathode, a tap for measuring the chamber pressure, and a gas supply opening. Argon gas is introduced through a perforated plate to ensure uniform distribution around the chamber. The front plate is provided with a water-cooled jacket into which replaceable copper anodes may be inserted. The anode used in this work was 1.50 in. long and had a diameter of 0.250 in. The cathode assembly consists of two concentric tubes, with cooling water flowing through the annulus, and a copper heat sink threaded on the end into which the tungsten cathode material is force fitted. The cathode assembly may be

moved axially to provide different arc gaps, and the arc gap was set so that the flow did not choke at the nozzle entrance. The gas inlet temperature is obtained from a copper-constantan thermocouple which is mounted in a copper tube to shield it from the arc region.

The arc-jet operating parameters which were measured and the instruments used for the measurements are shown in Table I (Appendix II).

2.3 FORCE MEASURING SYSTEM

A rotatable hollow shaft in the force measuring system (Fig. 3) transfers the force produced by the arc jet through the cell wall to the end of a small cantilever beam mounted outside the cell. A strain gage is attached to the beam to detect changes in deflection, and the output voltage is monitored on a strip-chart recorder. The arc jet is mounted in a vertical position, and all instrumentation and supply leads are brought outside the test cell through the center of the hollow shaft. This arrangement reduces drag produced by the leads and plumbing.

The force measuring system is calibrated by applying known weights to the arc jet and thus obtaining the response curve for the system. Points on the response curve may be repeated with a maximum error of ±3 percent.

2.4 PITOT PRESSURE PROBE

The high stagnation temperature which existed in the free jet necessitated cooling the pitot pressure probe. This was accomplished by constructing a water-cooled copper probe holder with a threaded inlet which would accept threaded probe tips made from copper tubing. This configuration allowed different probe tips to be used and still furnished enough cooling capacity so that the probe tips did not melt except at positions very near the nozzle exit. The probe holder with a tip installed is shown in Fig. 4. Two flat-faced probe tips were used. One tip had a 0.125-in. inside diameter and a 0.1875-in. outside diameter, and the other had a 0.195-in. inside diameter and a 0.250-in. outside diameter.

Horizontal movement of the probe was accomplished by mounting it on a hinge which could be moved from outside the test cell. The probe was aligned with the centerline of the nozzle exit, and, thus, an arc could be traced through the stream from edge to edge, passing through

the center of the gas stream. Vertical positioning was achieved by using a screw and a threaded block to which the probe was attached.

The pitot pressure was measured by a pressure transducer and recorded on a strip-chart recorder.

2.5 PROCEDURE

The operating characteristics of the arc jet and the impact pressure values were obtained as follows: The arc jet was started, and the gas flow rate and power input were set. After steady-state operation was reached, the impact pressures were measured by sweeping the probe slowly across the stream. The probe was then moved to another axial position, and the pressure was again obtained. After the desired number of axial positions were covered, the arc-jet operating parameters were measured. The same procedure was followed for different gas flow rates and different power input levels.

The input power ranged from 3 to 5 kw. Gas mass flow rates were from 0.00407 to 0.00585 lb/sec; chamber pressure ranged from 8.08 to 12.98 psia; and gas inlet temperature was on the average about 520°R. A complete listing of the measured quantities is given in Table II.

SECTION III
ANALYSIS

3.1 FLOW THROUGH THE ARC REGION

It was shown by Bryson and Fröhlich (Ref. 3) that the flow of argon gas through the arc region of a Gerdien-type d-c arc jet with a constant-area anode nozzle could be approximated by the one-dimensional, constant-area, heat-addition (Rayleigh heating) analysis. The important quantities which can be obtained from this analysis are the total temperature and total pressure at the exit of the nozzle. The equations for these quantities are given by Shapiro (Ref. 4) as

$$\left(\frac{T_{o_2}}{T_{o_1}}\right)_{RH} = \left(\frac{M_2^2}{M_1^2}\right)\left(\frac{1+\gamma M_1^2}{1+\gamma M_2^2}\right)^2 \left(\frac{1+\frac{\gamma-1}{2}M_2^2}{1+\frac{\gamma-1}{2}M_1^2}\right) \tag{1}$$

and

$$\left(\frac{p_{o_2}}{p_{o_1}}\right)_{RH} = \left(\frac{1+\gamma M_1^2}{1+\gamma M_2^2}\right)\left(\frac{1+\frac{\gamma-1}{2}M_2^2}{1+\frac{\gamma-1}{2}M_1^2}\right)^{\gamma/\gamma-1} \tag{2}$$

where the subscript 2 denotes the exit plane of the nozzle and the subscript 1 denotes the entrance. The Mach number at the entrance is given implicitly by the mass flow equation in the form

$$\frac{\dot{m}}{A} = \sqrt{\frac{\gamma}{R}} \frac{p_{o_1}}{\sqrt{T_{o_1}}} \frac{M_1}{\left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \tag{3}$$

It was shown in Ref. 3 that the degree of ionization for a similar arc jet under similar conditions is quite small (~2 percent) so that using the ideal value for the ratio of specific heats ($\gamma = 5/3$) is justified. The pressure ratio of arc-jet chamber pressure to test cell pressure is quite large (~150), and a large amount of heat is added to the gas; therefore, it is assumed that the flow is choked at the nozzle exit ($M_2 = 1$). With these assumptions and by using the measured parameters $\dot{m}$, A, p_{o_1}, and T_{o_1}, the total temperature and the total pressure at the nozzle exit may be found.

The Rayleigh heating analysis neglects friction or any other losses which might occur in the nozzle. To obtain more realistic values for the temperature and pressure at the nozzle exit, these losses must be included. Bryson (Ref. 2) studied a method by which the values of total temperature and total pressure obtained from the Rayleigh heating equations could be corrected by including a term which would account for the resistance force in the nozzle. This correction is introduced as a loss coefficient and is defined as

$$C_\ell = \frac{F_i - F_m}{F_i + p_c A} \tag{4}$$

where F_i is the thrust which would be produced under ideal conditions and F_m is the thrust actually produced by the arc jet.

The thrust produced by the arc jet can be written as

$$F = \dot{m} u_2 - A(p_2 - p_c) \tag{5}$$

With the use of the mass flow relation

$$\dot{m} = \rho A u \tag{6}$$

and the perfect gas relation

$$u = M \sqrt{\gamma R T} \tag{7}$$

and

$$p = \rho R T \tag{8}$$

Eq. (5) may be transformed into

$$F = p_2 A(1 + \gamma M_2^2) - p_c A \tag{9}$$

By use of the isentropic relation

$$\frac{p_o}{p} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma - 1}} \tag{10}$$

Eq. (9) may be further transformed into

$$F = p_{o_2} A \frac{1 + \gamma M_2^2}{\left(1 + \frac{\gamma - 1}{2} M_2^2\right)^{\gamma/\gamma-1}} - p_c A \tag{11}$$

Substituting Eq. (11) into Eq. (4) and dividing both sides by p_{o1} result in

$$\frac{p_{o_2}}{p_{o_1}} = (1 - C\ell)\left(\frac{p_{o_2}}{p_{o_1}}\right)_{RH} \tag{12}$$

Similarly, substituting Eq. (8) into Eq. (4); dividing both sides of the equation by T_{o1}; and using Eqs. (6), (7), and (8) and the ideal gas relation

$$\frac{T_o}{T} = \left(1 + \frac{\gamma - 1}{2} M^2\right) \tag{13}$$

will yield

$$\frac{T_{o_2}}{T_{o_1}} = (1 - C\ell)^2 \left(\frac{T_{o_2}}{T_{o_1}}\right)_{RH} \tag{14}$$

Equations (12) and (14) give the corrected values of total pressure and total temperature, respectively. The problem of defining the pressure and temperature of the gas at the nozzle exit is the one of determining the loss coefficient. This can be accomplished by measuring the thrust produced by the arc jet and determining the ideal thrust value by measuring the arc-jet chamber conditions. Values of the ideal and measured thrust are shown in Fig. 5.

Because of the scatter in the values of measured thrust introduced by error in the force measuring system, Bryson (Ref. 2) introduced an approximate form of Eq. (4). Substituting Eq. (2) into Eq. (11) gives

$$F = p_{o_1} A \frac{1 + \gamma M_1^2}{\left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\gamma/\gamma-1}} - p_c A \tag{15}$$

The heat addition in the nozzle causes the entrance Mach number to be quite small (~0.2); therefore, Eq. (15) can be approximated by

$$F \approx (\text{constant})\, p_{o_1} - p_c A \tag{16}$$

A least-squares fit of the values of thrust and chamber pressure to Eq. (16) will give the straight lines shown in Fig. 5. Substitution of these relations for the thrust into Eq. (4) will yield the approximate form

$$C_\ell \approx \frac{(m-n)\, p_{o_1} + (a-b)}{m\, p_{o_1} + (a - p_c A)} \tag{17}$$

where m and n are the slopes of the lines representing the ideal thrust and the measured thrust, respectively, and a and b are the intercepts on the thrust axis. By writing the loss coefficient in this form, the errors in the thrust measurement should be averaged out. The values of the loss coefficient are shown in Fig. 6, and the approximation given by Eq. (17) is also shown in Fig. 6 as the solid line. For comparison, error bounds are shown as dotted lines. These were formed by introducing the ±3-percent error in the measured thrust into Eq. (17). Figure 6 indicates that greater accuracy in the thrust measurement technique would be required to reduce the scatter in the measured values of the loss coefficient.

Total temperatures and total pressure determined by the use of the loss coefficient should be more accurate than those determined by the Rayleigh heating analysis because allowance is made for losses in the nozzle. In applications where the thrust cannot be measured conveniently, the use of the given loss coefficient will allow determination of approximate values for the total temperature and total pressure at the nozzle exit of arc jets of similar design. Figure 7 gives a comparison of total temperatures determined by the Rayleigh heating analysis, by the measured thrusts, and by the average values of the loss coefficient. These values are shown as functions of the flow parameter

$$z = \sqrt{\frac{R}{\gamma}}\,\frac{\dot{m}}{A}\,\frac{\sqrt{T_{o_1}}}{p_{o_1}} = \frac{M_1}{\left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{\frac{\gamma + 1}{2(\gamma - 1)}}} \tag{18}$$

obtained from the mass flow equation. Figure 8 gives a similar comparison of the values of total pressure.

3.2 THE EXPANDED GAS STREAM

Gas properties at the arc-jet nozzle exit, determined by the method discussed in Section 3.1, can be used as the starting point for a method

of characteristics solution of the potential flow equations. If gas properties from this solution can be shown to agree with those measured in the actual flow field, the starting conditions are adequate approximations.

The most easily measured quantity in the expanded gas stream is the pitot or impact pressure. Therefore, the simplest method of making a comparison between the actual flow field and that given by the potential flow theory is through the pitot pressure. A shock wave is developed in front of a pitot tube placed in a supersonic flow. Therefore, the pressure sensed by the tube is the stagnation or total pressure downstream of the shock wave. On the stagnation streamline, the shock is normal, and the ratio of measured pitot pressure to upstream total pressure is given by the Rayleigh pitot equation and is listed in Liepmann and Roshko (Ref. 5) as

$$\frac{p_{o_y}}{p_{o_x}} = \left(\frac{2\gamma}{\gamma+1} M_x^2 - \frac{\gamma-1}{\gamma+1}\right)^{-\frac{1}{\gamma-1}} \left(\frac{\frac{\gamma+1}{2} M_x^2}{1 + \frac{\gamma-1}{2} M_x^2}\right)^{\frac{\gamma}{\gamma-1}} \tag{19}$$

where M_x is the Mach number ahead of the normal shock. Thus, if the Mach number is known, the total pressure upstream of the shock can be determined. Conversely, if the upstream total pressure is known, the Mach number can be determined.

The Mach number distribution in the expanded stream is furnished by a method of characteristics solution of the potential flow equations. Any practical method of characteristics computation requires the use of a digital computer. A number of characteristic computer programs have been developed by other investigators, and thus it was not necessary to develop a new program for the present investigation. However, a great deal of time was spent in attempting to accurately calculate Mach numbers at positions as far downstream of the nozzle exit as 18 nozzle radii. The failure to obtain good results was caused by the accumulation of errors in the numerical procedures used. The program finally chosen for use in this case was developed recently by J. H. Fox (Ref. 6), and was chosen because computational errors did not become large in the downstream direction. Mach numbers along the centerline of the gas stream obtained from this computer solution are given in Fig. 9. Mach numbers along the centerline given by measured pitot pressure and Eq. (19) are also included in Fig. 9.

Radial Mach number profiles at various axial positions are compared in Fig. 10. The experimental profiles were obtained from the

measured pitot pressures, and the profiles from the method of characteristics solution were determined by linear interpolation along characteristic lines. These profiles were terminated at radii where the angle between the pitot pressure probe and the local flow direction had reached approximately 20 deg. This was done because the accuracy of the pressure measurement decreases when this angle becomes large (Ref. 5).

The method of characteristics program used in this study required a large amount of computer time for each run; therefore, it was not possible to obtain a solution for each particular set of arc-jet operating conditions. However, since centerline Mach numbers should be least affected by variations in nozzle exit conditions, it would be advantageous to compare the solution given previously in Fig. 9 with centerline Mach numbers determined from measured pitot pressures for a variety of arc-jet operating conditions. This comparison is made in Fig. 11. Even though there is a tendency for the measured values to be somewhat lower than the characteristics values, the agreement is within 7 percent.

Ashkenas and Sherman (Ref. 7) developed a relation for the Mach number distribution along the centerline of a free jet based on source flow considerations. In Fig. 12, this relation is compared with the characteristics solution from Fig. 9 and Mach numbers obtained by averaging all the experimentally determined values. As can be seen, the disagreement between the source flow relation and the averaged data values is somewhat larger than that for the characteristics solution.

3.3 DISCUSSION OF ERRORS

The shock wave in front of a blunt body placed in a supersonic flow is detached from the body and stands a finite distance ahead of the body (Ref. 5). The pressure sensed by a pitot tube is the stagnation pressure behind the shock wave. The upstream Mach number calculated from this pressure is assumed to occur at the probe tip in plotting the data in Fig. 11. This Mach number actually occurs ahead of the probe tip a distance equal to the shock standoff distance. Although no values of shock standoff distance were determined in this study, the inclusion of such distances would tend to shift the experimental values in Fig. 11 toward the theoretical solution. Superimposed on these errors caused by the shock standoff distance are other errors also of a position nature. These arise because the axial position of the probe was determined by a pointer and scale read by eye. This procedure introduced small errors in determining the probe tip position and is believed to be partly responsible for the scatter exhibited in the experimental points in Fig. 11.

Other sources of error are readily apparent when analyzing such a gas stream. Because the flow is low density, there is a possibility of probe lip effects (Ref. 8). However, data were obtained with probes of different diameters, and no difference in pressure readings were detected. Another possible source of error involved is related to the amount of energy which is contained in the excited and ionized states in the gas (Ref. 3). If a portion of this energy were released as kinetic energy downstream of the arc-jet nozzle exit, it would have the effect of lowering the Mach number somewhat (Ref. 9). No attempt was made at investigating this process; however, the small errors involved would indicate that it is of a small magnitude if it does exist.

The losses which occur in the arc-jet nozzle partly result from friction. This being the case, a boundary layer should form in the nozzle and alter the velocity profile to some extent. A uniform profile was considered in the method of characteristics solution; therefore, some error was possibly introduced into the calculation because of incorrect initial conditions in starting the theoretical solution.

SECTION IV
CONCLUDING REMARKS

The good agreement between the predicted and measured Mach numbers throughout the core of the expanded gas stream indicates that the method used to determine the argon gas properties at the exit of the arc jet can be used as a first approximation. Since the assumption was made that $\gamma = 5/3$ in the calculation of the flow properties, the agreement also indicates that the energy which is contained in the gas in excited or ionized states does not appreciably affect the flow properties. However, power inputs considerably greater than those used in this investigation would cause larger degrees of ionization, and internal forces might develop which would alter the flow field.

The method of characteristics program (Ref. 6) used in this study to solve the potential flow relations and determine the Mach number distribution in the free jet will yield values of Mach number which differ from the averaged measured values by about 4 percent. This difference would cause errors in calculating the static temperature and static pressure of about 8 and 18 percent, respectively. Average Mach numbers along the centerline of the free jet may be predicted within about 6 percent by use of the source flow relation given in Ref. 7. This allows a much faster determination of Mach numbers than the method of characteristics solution of the potential flow equations; however, the source

flow relation may be applied only in the case of a sonic nozzle. The method presented here for determining the gas properties at the arc-jet nozzle exit could be extended to account for slightly diverging or slightly converging nozzles.

The results of this study indicate that the bulk properties of the argon gas stream produced by a d-c arc jet may be determined by using conventional gasdynamic relations. The flow through the arc region may be characterized by the ideal, one-dimensional, constant-area, heat-addition relations with the inclusion of a correction to account for losses suffered in the anode nozzle. The gas properties in the inviscid core may be obtained by use of the ideal, potential flow relations (specifically, the axisymmetric method of characteristics solution of the potential flow relations). The important feature is that after correction factors have been established, one need only monitor the gas flow rate, the gas inlet temperature, and the arc-jet chamber pressure in order to determine the gas properties throughout the stream.

REFERENCES

1. McGregor, W. K. and Brewer, L. E. "Spectroscopy of Supersonic Plasma: III. Electron Temperature Measurements in Argon Plasma by Two Independent Methods." AEDC-TR-65-131 (AD473660), November 1965.
2. Bryson, R. J. "Anode Nozzle Effects on the Bulk Properties of Arc-Heated Argon." AEDC-TR-68-106 (AD670511), June 1968.
3. Bryson, R. J. and Fröhlich, J. P. "Study of the Energy Addition Process in a D-C Arc-Jet." AEDC-TR-65-268 (AD631591), April 1966.
4. Shapiro, A. H. The Dynamics and Thermodynamics of Compressible Fluid Flow. Vol. 1. The Ronald Press Company, New York, 1953.
5. Liepmann, H. W. and Roshko, A. Elements of Gasdynamics. John Wiley and Sons, Inc., New York, 1957.
6. Fox, J. H. "An Axially Symmetric, Inviscid, Real Gas, Non-Isoenergetic Flow Solution by the Method of Characteristics." Unpublished Master's Thesis, The University of Tennessee, Knoxville, 1968.

7. Ashkenas, H. and Sherman, F. S. "The Structure and Utilization of Supersonic Free Jets in Low Density Wind Tunnels." Fourth Symposium on Rarefied Gas Dynamics. Academic Press, New York, 1966.

8. Bailey, A. B. "Further Experiments on Impact-Pressure Probes in a Low-Density, Hypervelocity Flow." AEDC-TDR-68-208 (AD290520), November 1962.

9. Chou, Y. S. and Talbot, L. "Source-Flow Expansion of a Partially Ionized Gas into a Vacuum." AIAA Journal, Vol. 5, No. 12, December 1967, pp. 2166-2172.

APPENDIXES

I. ILLUSTRATIONS

II. TABLES

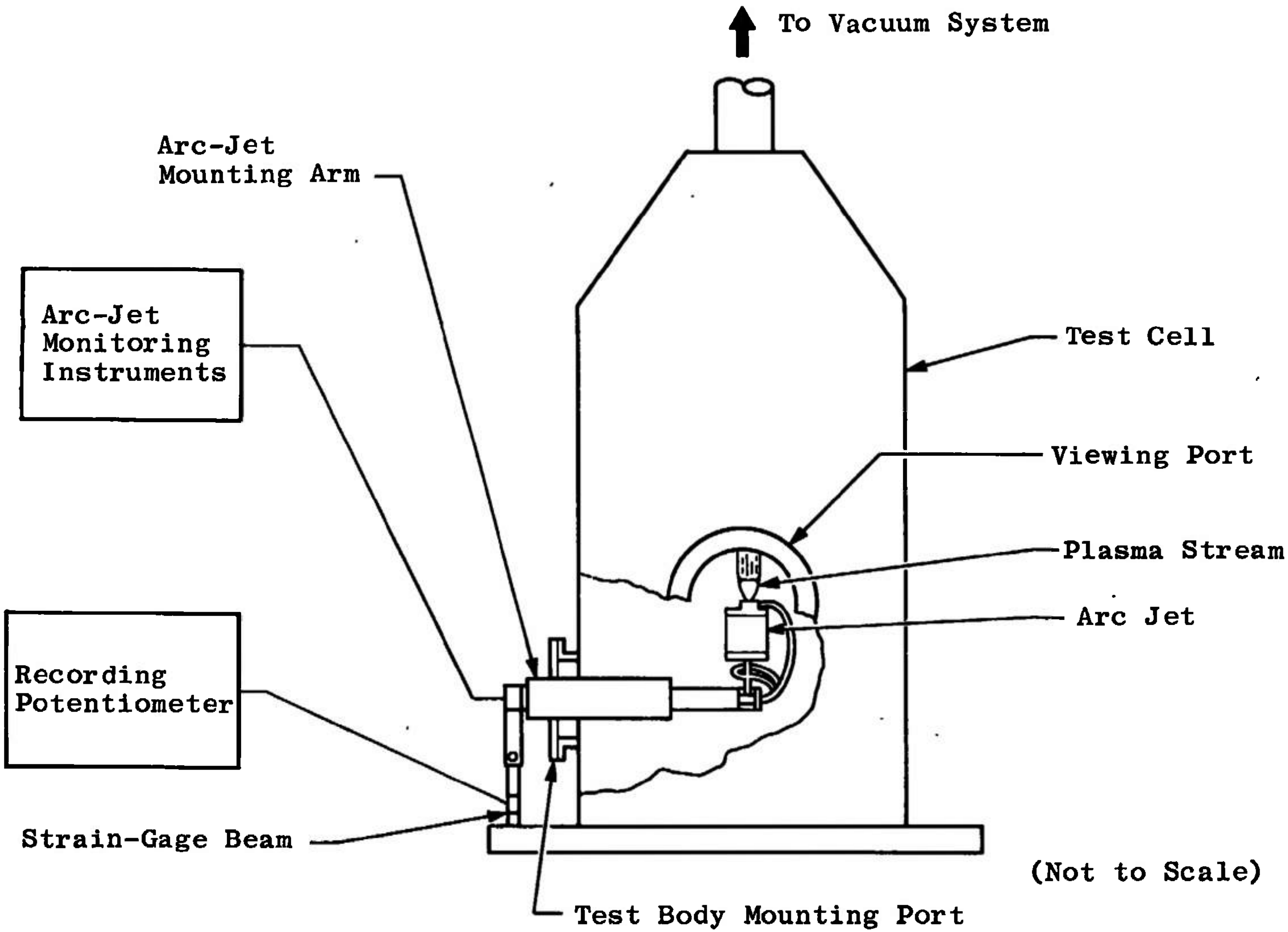
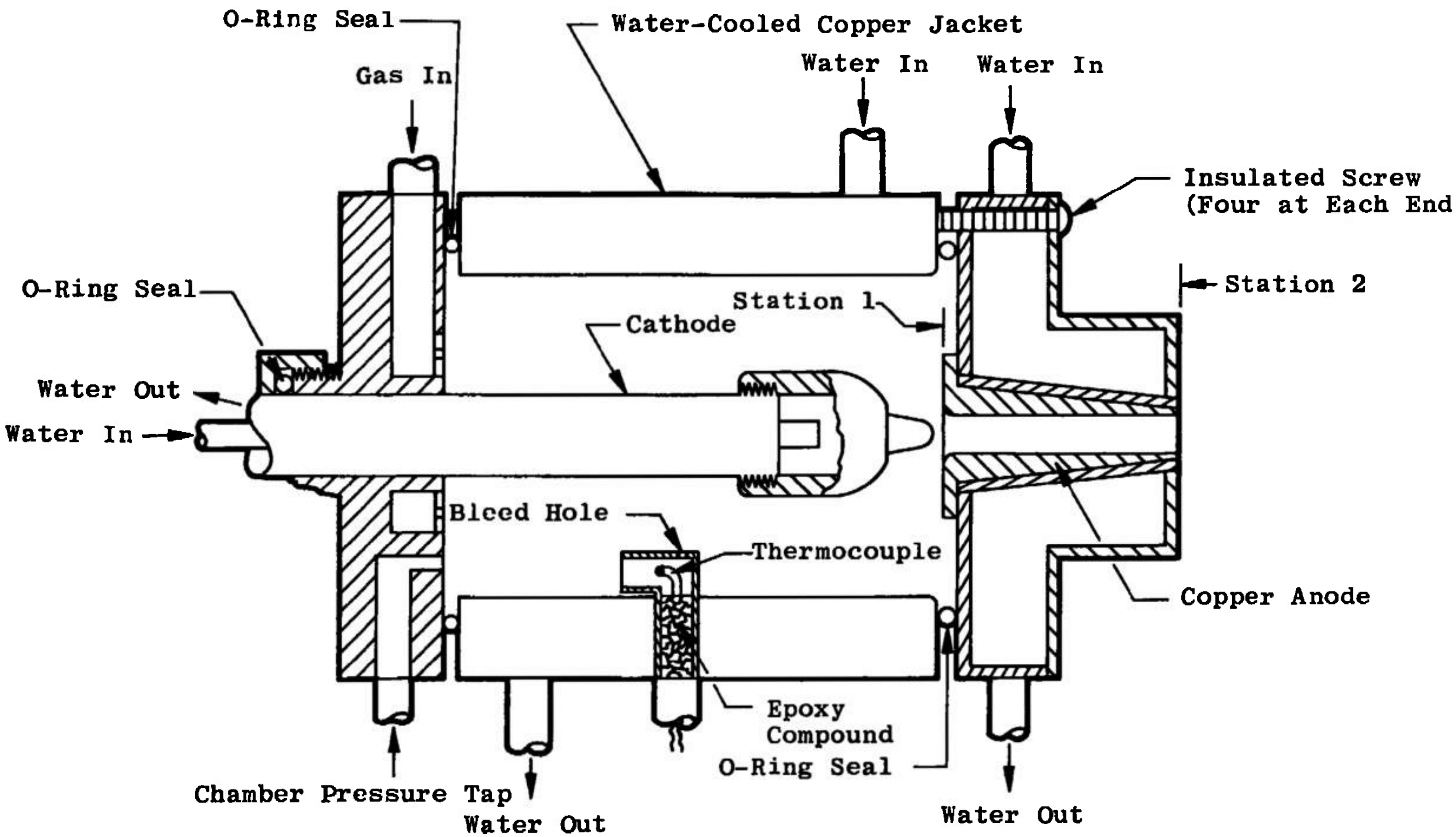


Fig. 1 Test Cell



(Not to Scale)

Fig. 2 Arc Jet

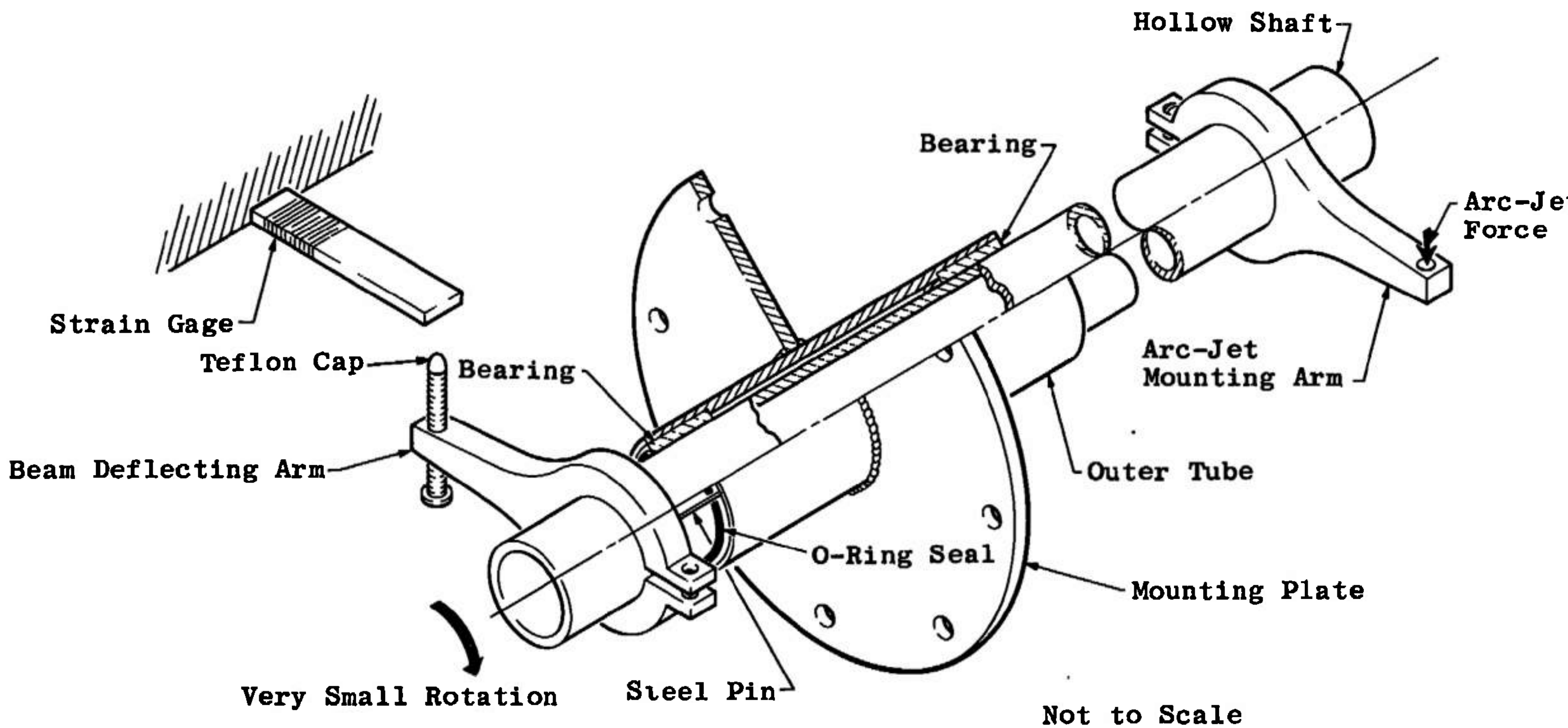


Fig. 3 Force Measuring System

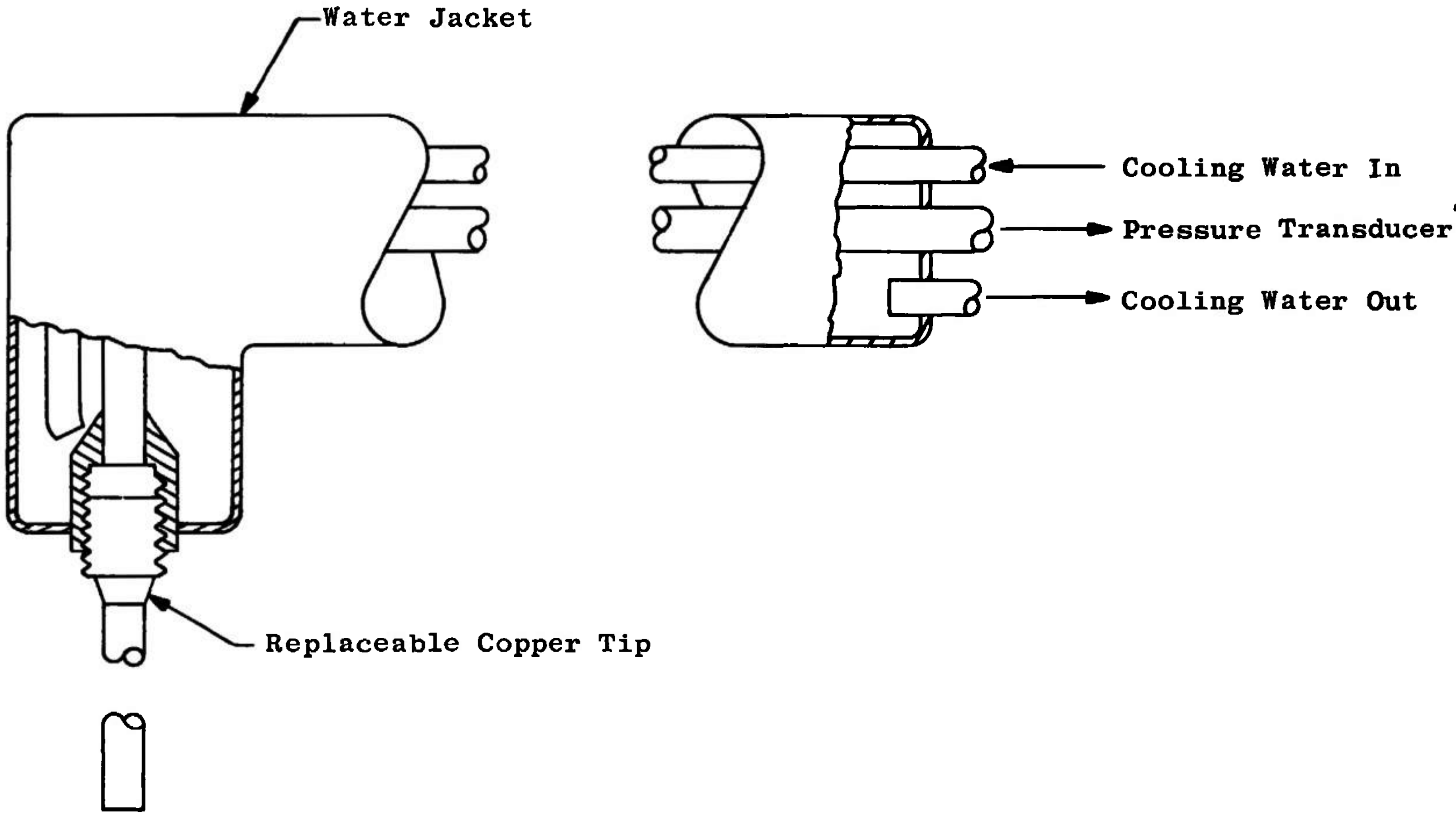


Fig. 4 Pitot Pressure Probe

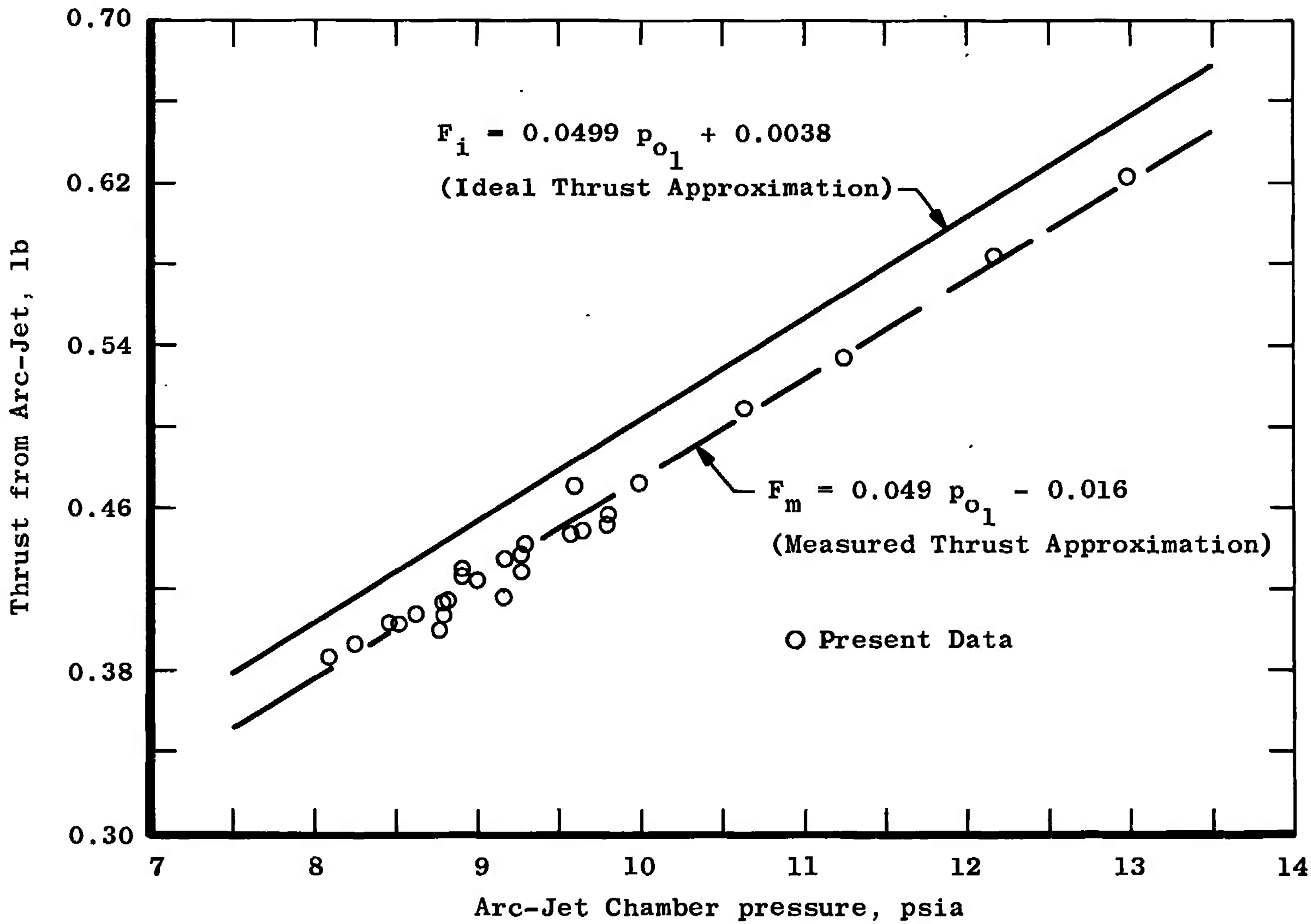


Fig. 5 Comparison of Ideal and Measured Thrust

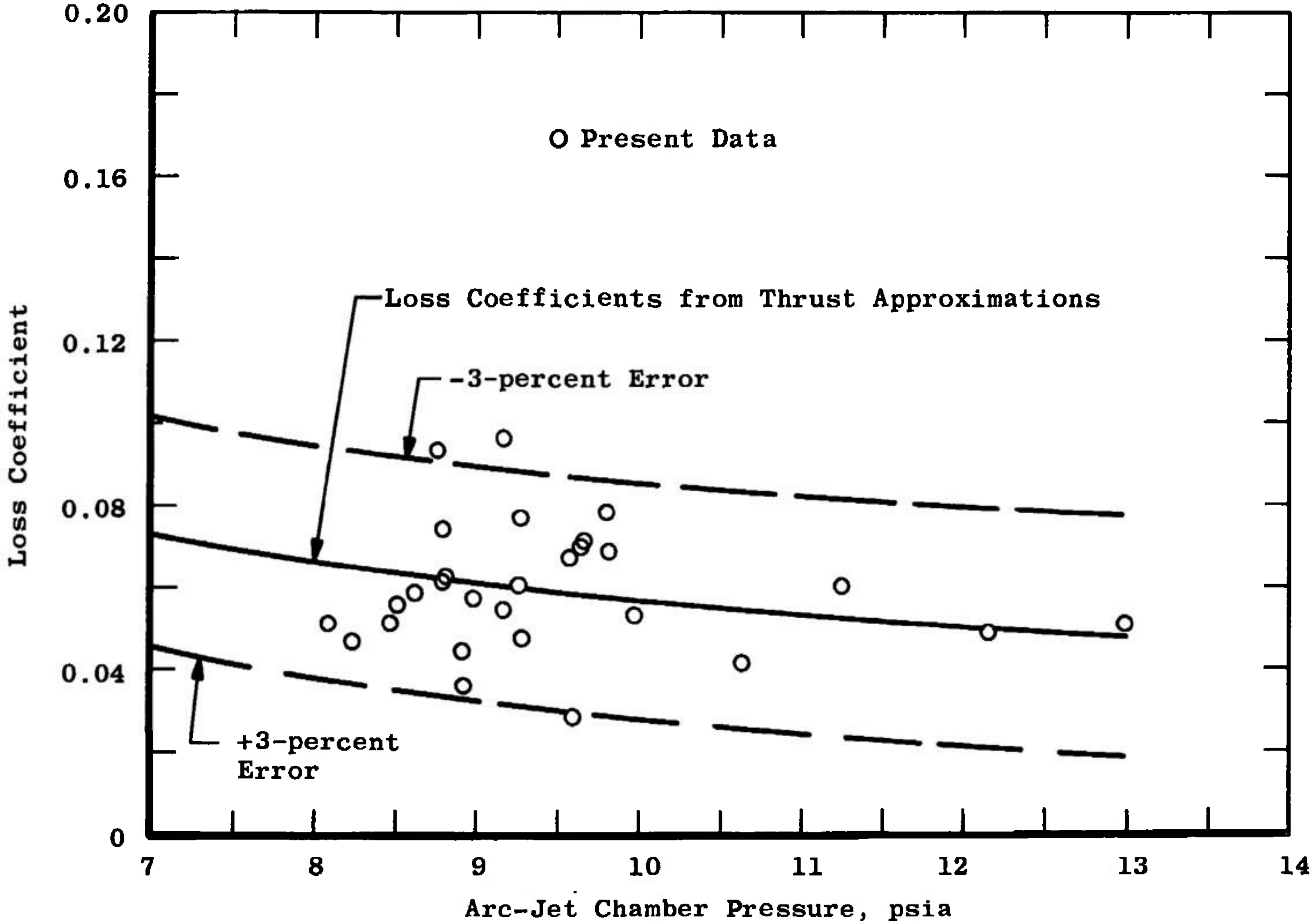


Fig. 6 Comparison of Measured Loss Coefficients with Those Obtained by Linear Approximations of Thrust

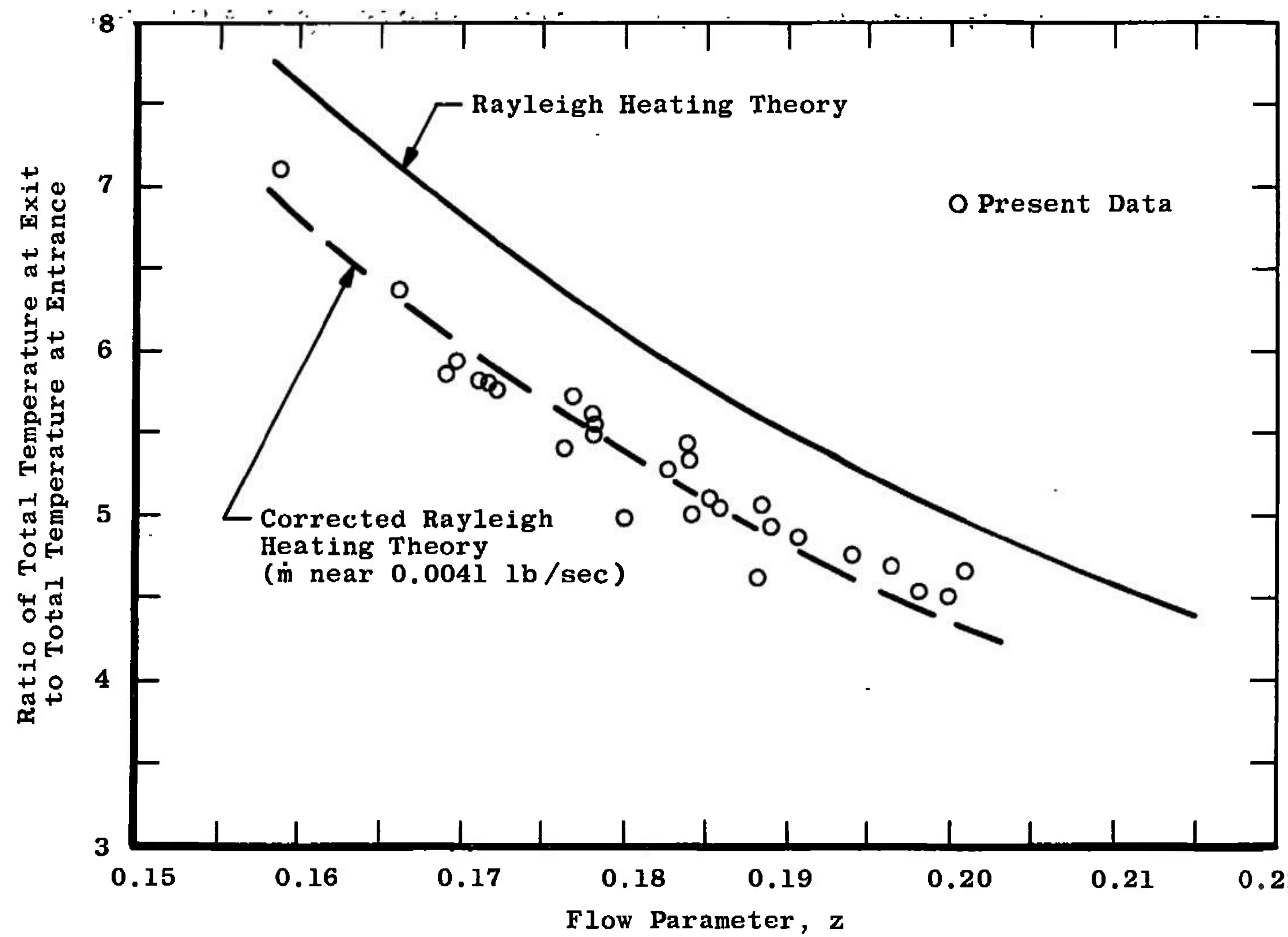


Fig. 7 Measured Total Temperature Increase in the Nozzle Compared with That Predicted by Rayleigh Heating Theory

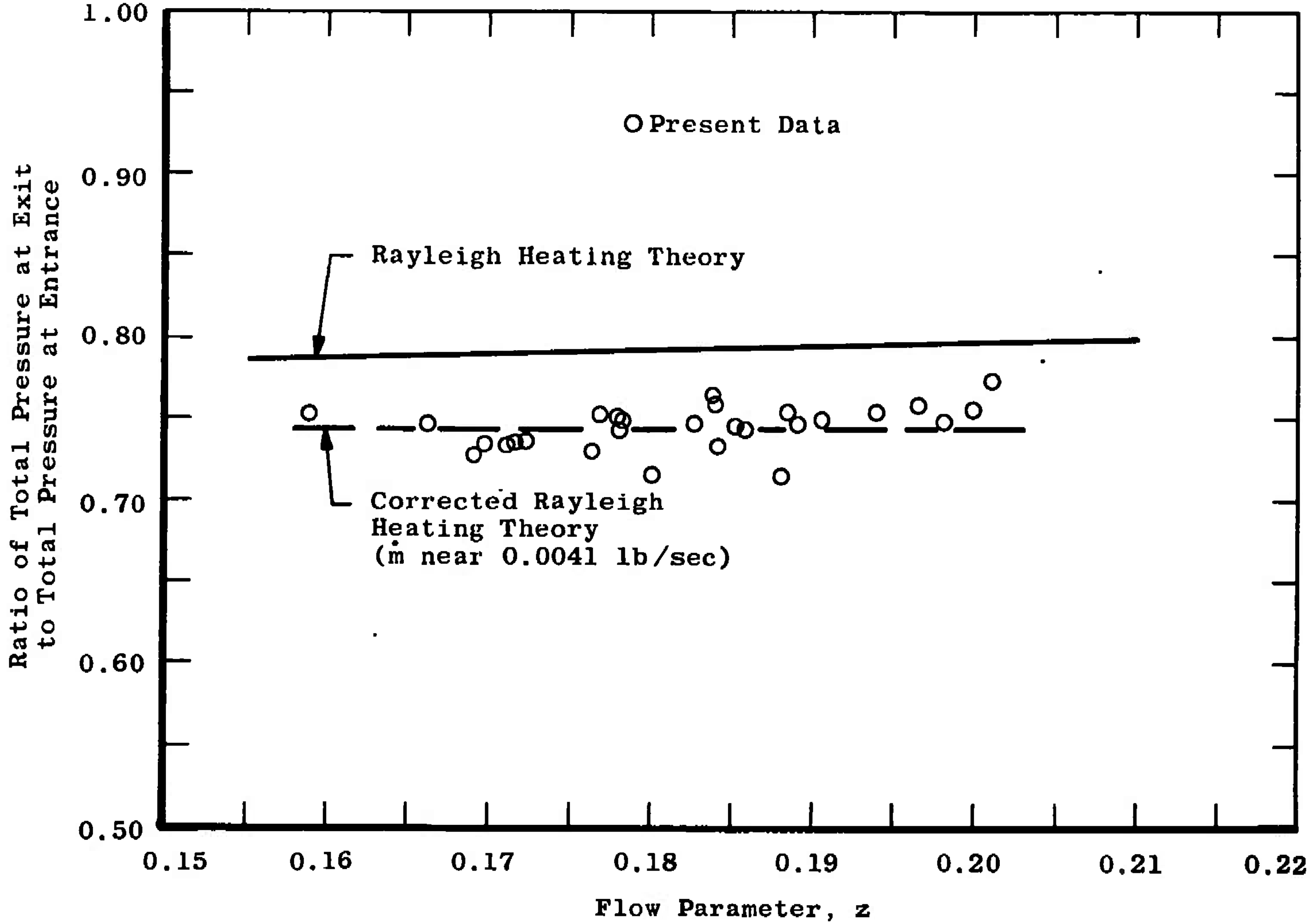


Fig. 8 Measured Total Pressure Drop in the Nozzle Compared with That Predicted by Rayleigh Heating Theory

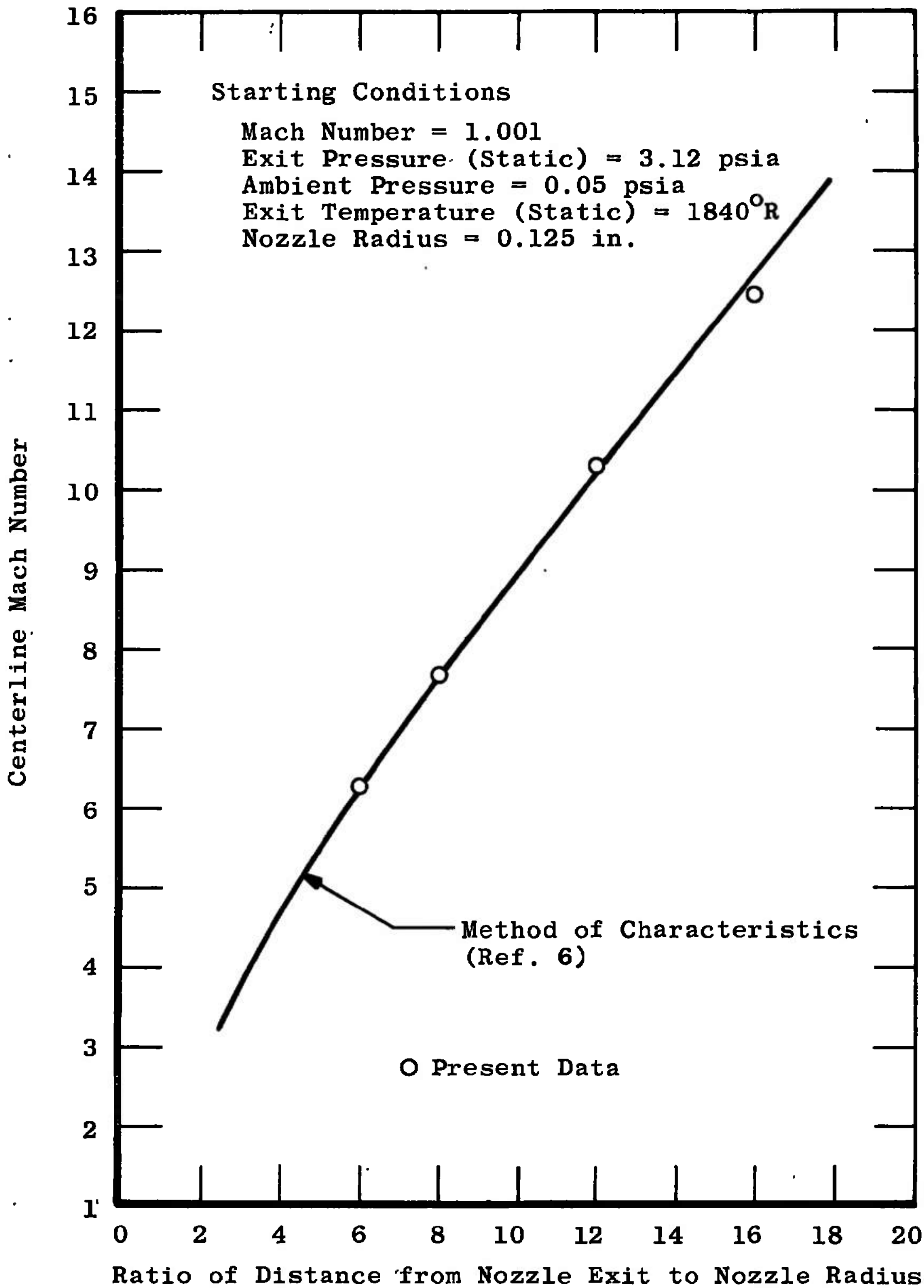


Fig. 9 Comparison of Measured Centerline Mach Numbers with Those Obtained from the Method of Characteristics

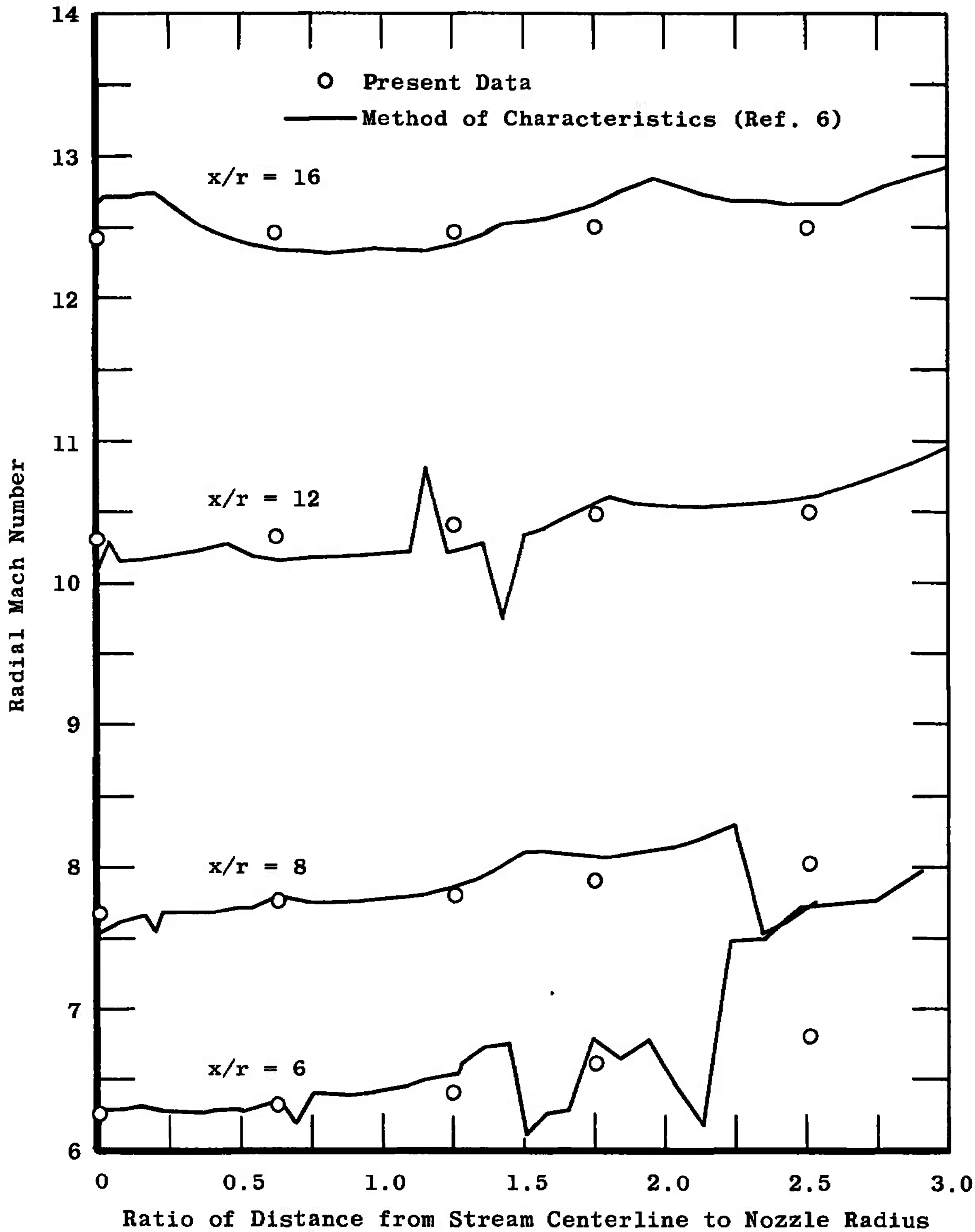


Fig. 10 Comparison of Measured Radial Mach Numbers with Those Obtained from the Method of Characteristics

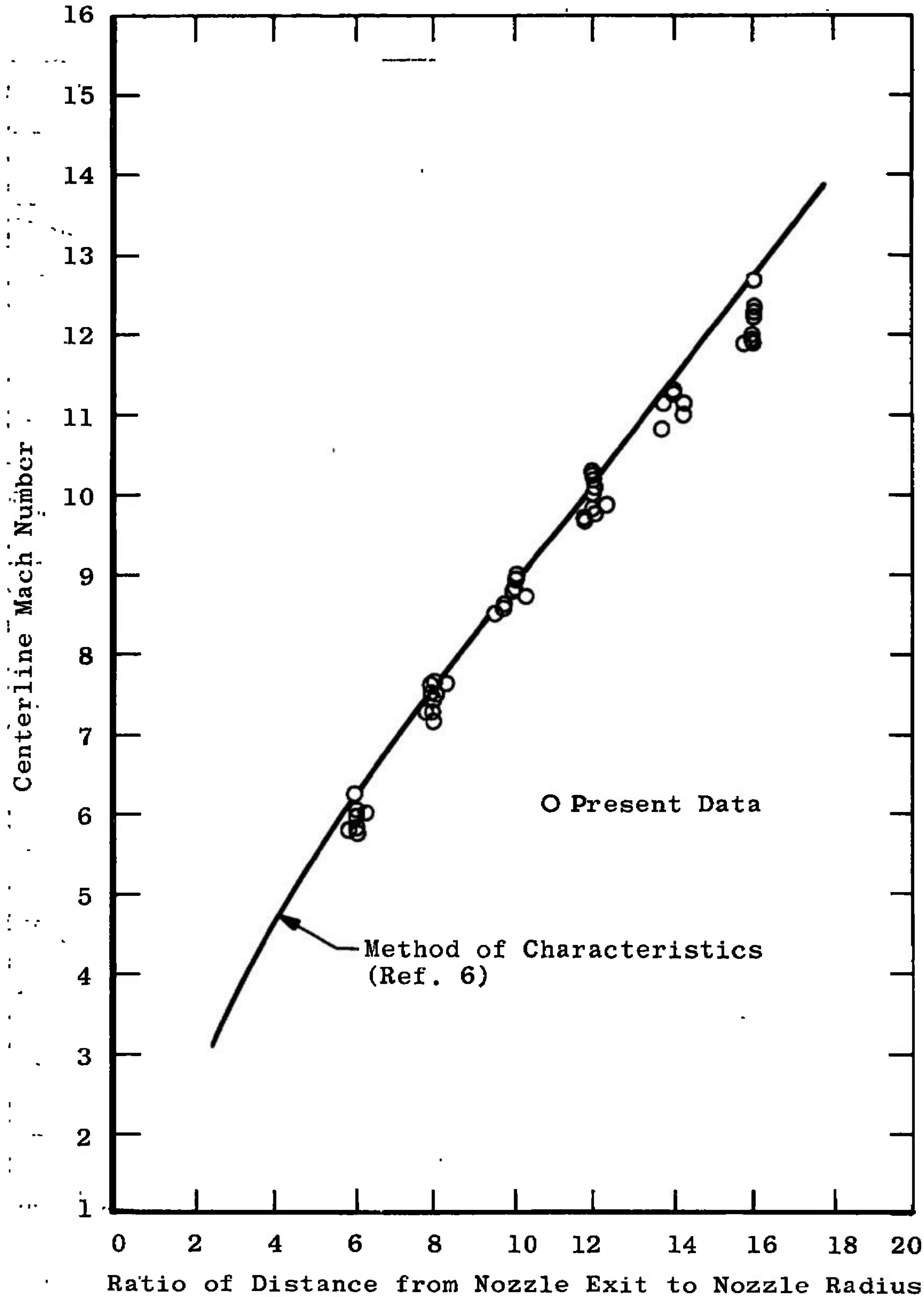


Fig. 11 Comparison of Measured Centerline Mach Numbers for a Variety of Arc-Jet Conditions with Those from the Method of Characteristics

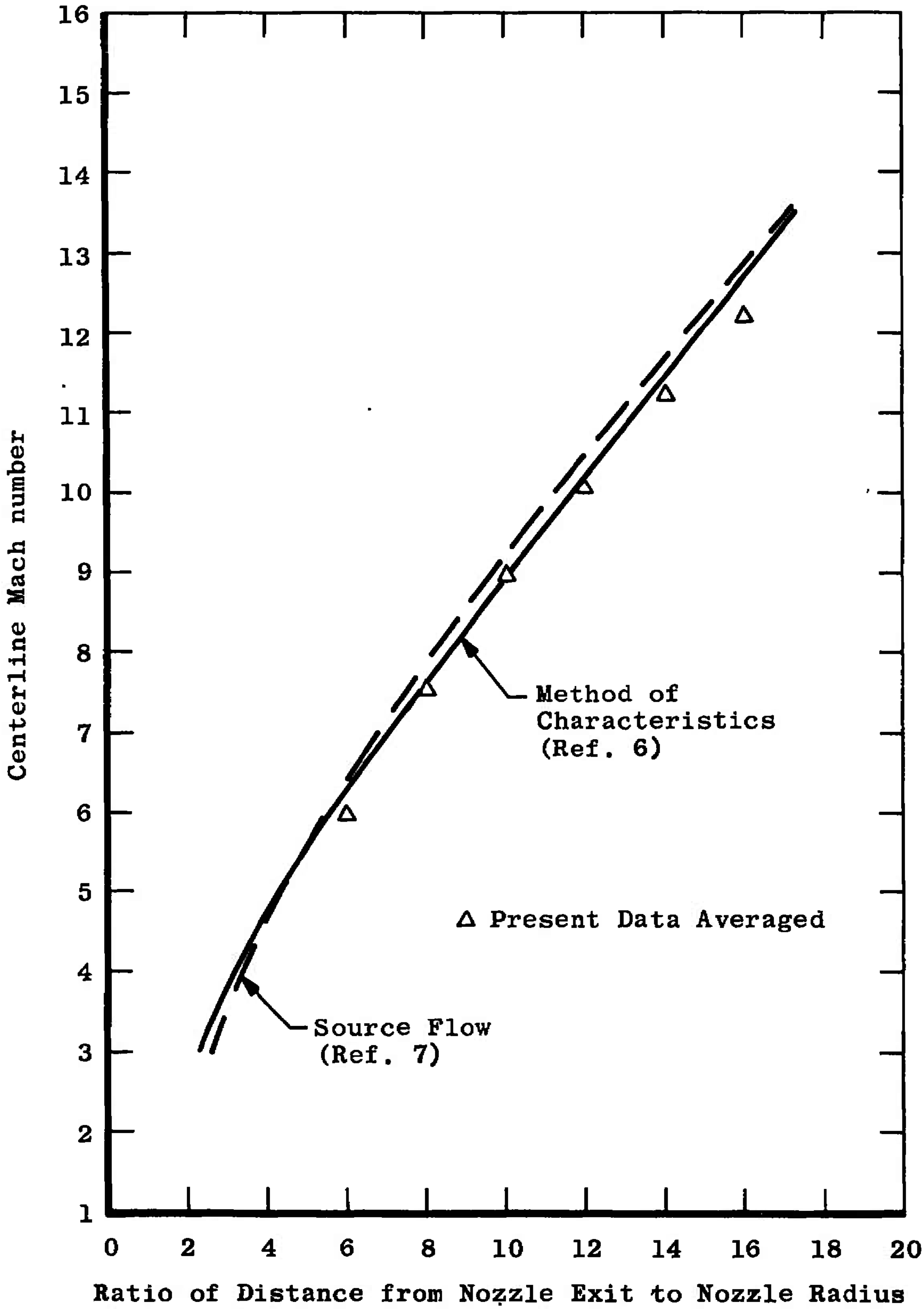


Fig. 12 Comparison of Averaged Measured Centerline Mach Numbers with Those from the Method of Characteristics and Those from Source Flow

TABLE I
INSTRUMENTS USED TO MEASURE ARC-JET OPERATING CONDITIONS

Parameter Measured	Instrument and Range	Maximum Error in Measurement, percent
Gas Flow Rate	Brooks Rotameter 0 to 10 scfm	2.0
Gas Inlet Temperature	Copper-Constantan Thermocouple	1.0
Arc-Jet Chamber Pressure	Pressure Transducer and Strip-Chart Recorder 0 to 100 psid	0.5
Arc Potential	Strip-Chart Recorder	1.0
Arc Current	Shunt and Strip-Chart Recorder	1.0
Test Cell Pressure	McLeod Gage	4.0

TABLE II
EXPERIMENTAL DATA

Point	$\dot{m}$, lb_m/sec	p_{o1}, $lb_f/in.^2$	T_{o1}, °R	p_c, $lb_f/in.^2$	Arc Current, amp	Arc Potential, v	F_m, lb_f	x/r	Pitot Pressure, $lb_f/in.^2$
1	0.00422	9.26	510	0.0484	97.5	39.4	0.437	9.74 11.74 13.74 15.74	0.226 0.158 0.107 0.089
2	0.00426	9.82	510	0.0484	117.0	37.5	0.458	5.76 7.74 9.74 11.74 13.74	0.662 0.370 0.232 0.167 0.121
3	0.00420	8.46	509	0.0484	103.0	39.1	0.405	6.00 8.00 12.00 16.00	0.498 0.288 0.126 0.073
4	0.00422	8.76	513	0.0503	105.5	37.1	0.400	6.24 8.26 14.26	0.542 0.287 0.102
5	0.00422	9.16	514	0.0503	127.8	35.1	0.417	8.26 10.26 12.26 14.26	0.300 0.204 0.144 0.102
6	0.00411	8.78	516	0.0484	103.5	39.6	0.408	6.00 8.00 10.00	0.563 0.302 0.195
7	0.00419	9.64	520	0.0503	124.0	39.3	0.449	6.00 8.00 10.00 12.00 14.00 16.00	0.586 0.323 0.206 0.146 0.108 0.075
8	0.00585	12.98	520	0.0580	123.0	40.1	0.623	8.00 10.00 12.00 14.00 16.00	0.450 0.284 0.191 0.147 0.114
9	0.00582	12.16	519	0.0580	102.0	41.3	0.584	8.00 10.00 12.00	0.422 0.261 0.182

TABLE II (Concluded)

Point	$\dot{m}$, lb_m/sec	p_{o1}, $lb_f/in.^2$	T_{o1}, °R	p_c, $lb_f/in.^2$	Arc Current, amp	Arc Potential, v	F_m, lb_f	x/r	Pitot Pressure, $lb_f/in.^2$
10	0.00417	8.81	513	0.0484	100.3	41.0	0.415	8.00	0.323
11	0.00417	8.91	513	0.0484	100.2	41.1	0.431	6.00	0.647
12	0.00419	8.91	512	0.0484	100.4	41.1	0.428	8.00	0.321
13	0.00415	9.57	530	0.0445	139.4	34.2	0.448	8.00	0.327
14	0.00411	9.17	529	0.0445	120.5	34.4	0.436	8.00	0.317
15	0.00410	8.62	528	0.0445	101.0	35.0	0.408	8.00	0.298
16	0.00407	8.08	527	0.0445	82.5	36.3	0.387	8.00	0.285
17	0.00486	9.60	526	0.0503	99.5	35.0	0.471	8.00	0.339
18	0.00412	9.28	529	0.0445	111.0	36.9	0.443	6.00 8.00 12.00 16.00	0.670 0.362 0.156 0.087
19	0.00417	9.99	529	0.0445	128.0	36.4	0.473	6.00 8.00 12.00 16.00	0.695 0.389 0.167 0.095
20	0.00413	8.98	527	0.0445	92.0	38.6	0.425	6.00 8.00 12.00 16.00	0.626 0.360 0.154 0.086
21	0.00422	10.63	535	0.0426	126.0	35.9	0.509	8.00	0.389
22	0.00413	9.65	533	0.0425	136.0	34.3	0.449	8.00	0.344
23	0.00415	9.80	532	0.0425	135.0	34.3	0.453	16.00	0.089
24	0.00410	9.27	530	0.0425	117.0	34.9	0.429	16.00	0.086
25	0.00408	8.78	530	0.0425	99.0	35.9	0.414	16.00	0.081
26	0.00407	8.23	527	0.0425	81.5	37.7	0.393	12.00 16.00	0.130 0.076
27	0.00408	8.51	528	0.0445	91.5	36.3	0.404	6.00 8.00 12.00 16.00	0.534 0.296 0.130 0.075
28	0.00570	11.24	510	0.0542	102.0	43.2	0.535	9.50	0.289

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Arnold Engineering Development Center ARO, Inc., Operating Contractor Arnold Air Force Station, Tennessee	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP N/A

3. REPORT TITLE

A METHOD FOR DETERMINING THE BULK PROPERTIES OF ARC-HEATED ARGON

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
July 1967 to September 1968 - Final Report

5. AUTHOR(S) *(First name, middle initial, last name)*

R. J. Bryson, ARO, Inc.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1969	36	9

8a. CONTRACT OR GRANT NO. F40600-69-C-0001 b. PROJECT NO. 8951 c. Program Element 61102F d. Task 05	9a. ORIGINATOR'S REPORT NUMBER(S) AEDC-TR-69-125 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* N/A

10. DISTRIBUTION STATEMENT
This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES Available in DDC	12. SPONSORING MILITARY ACTIVITY Arnold Engineering Development Center (AET) Arnold Air Force Station, Tennessee

13. ABSTRACT
The total temperature and total pressure of argon gas at the exit of a direct-current arc jet are determined by using a corrected version of the one-dimensional, constant-area, heat-addition analysis. The corrections are formulated in terms of the thrust produced by the arc jet and are determined by measuring the actual thrust. To assess the validity of properties determined in this manner, a method of characteristics solution of the general potential flow equations was obtained for the flow field resulting from a free expansion of the gas from these properties into a low pressure. Mach numbers given by this solution were then compared with those derived from measured pitot pressures in the expanded stream. The agreement between the predicted and the average measured values of Mach number is within about 4 percent. This would allow the average static temperature to be predicted within about 8 percent and the average static pressure to be predicted within about 18 percent. This indicates that the method of predicting the gas properties at the exit of the arc jet can be used as a first approximation.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
argon						
thermodynamic properties						
pressure measurement						
temperature measurement						
plasma devices						

2. Argon -- Properties

3. Arc heated argon

4-11

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